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Experimental Database on pullout bond performance of steel fiber embedded in ultra-high-strength concrete

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ABSTRACT

The bond strength between the steel fiber and the ultra-high performance concrete (UHPC) matrix plays a significant role in improving the behavior of plain UHPC. This paper compiles the existing experimental research database on the pullout bond performance of steel fibers embedded in UHPC. The variations of key parameters in the database are the steel fiber type and geometry, fiber volume fractions, and fiber embedded length. The effects of these parameters are analyzed and discussed in detail. Based on the analysis of the results, it was found that the deformed steel fibers, i.e., the hooked-end, half-hooked-end, and twisted steel fibers clearly provided higher average bond strengths than that straight fibers. The average pullout bond strength was obtained by increasing of fiber volume fraction in the UHPC matrix up to 2% (11.21MPa) with an increment of 20.4%. When the steel fiber volume fractions increase beyond 2%, the average bond strength decreases. Additionally, it was also found that using smaller embedded lengths in deformed steel fibers could result in the improvement of bond strength. This could be due to the fact that the bond is controlled by the mechanical anchorage of the end-hook rather than the physio-chemical bond in the straight portion. Conversely, increasing the embedded length of steel fiber could greatly contribute to the enhancement of pullout resistance resulting in increased bond strength between the UHPC matrix and steel fibers.

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1.0 Introduction

Many structures, such as nuclear power plants and industrial plants, are expected to be subjected to exposure to high temperatures because of their nature of operation [1]. Special structures such as nuclear power plants, high-rise buildings, and military protective structures are subjected to security problems of being exposed to a potentially high risk of terrorist attacks or accidental impact loads [2]. Additionally, some structures, such as tunnels and high-rise buildings, can be accidentally exposed to thermal danger that threatens the safety of people and causes severe property damage. Other structures, such as military structures, have a high potential for exposure to terrorist attacks or higher impact loads [1]. Therefore, this motivated the need for special concrete materials for these impact- and blast-resistant constructions in both civil and military sectors [3, 4]. Ultra-high performance fiber reinforced concrete (UHP) has been introduced as one of the most promising materials to be used in the construction of special security structures. Reactive powder concrete (RPC) was first developed by Richard and Cheyrezy [5] in the mid-1990s and is a precursor of ultra-high-performance concrete ((UHPC), recently available in several countries in Europe, North America, and Asia [6–9].

Ultra-high-performance concrete (UHPC) is a special type of concrete having very high strength, and it is composed of fine particles with diameters of less than 0.5 mm without coarse aggregate. The American Concrete Institute (ACI) committee 239 [7] described ultra-high-performance concrete (UHPC) as concrete that has a minimum compressive strength of 150 MPa and meets specified durability, tensile ductility, and toughness requirements. It is a new class of materials typically characterized by the high content of cementitious materials (800–1200 kg/m^3), and a water-to-cementitious material (W/CM) ratio of 0.20 ± 0.02 [10]. But in recent years, researchers have succeeded in reducing the cement dosage by using supplementary cementitious materials like fly ash, silica fume, ground furnace slag, etc. [11–13] to partially replace cement. Properly designed ultra-high performance concrete (UHPC) can deliver high flowability with self-consolidation, high strength and toughness, superior durability, and self-healing ability [14, 15]. The high strength of UHPC is generally achieved thru combining small aggregate sizes (less than 0.6-mm in diameter) with a cementitious matrix augmented with ultra-fine particles and pozzolanic admixtures. However, the extreme brittleness of the plain UHPC matrix results in a weakening of the resisting tensile stress and very low tensile strength [16–18]. Therefore, fiber reinforcement is necessary for any practical structural application.

To develop a better-performing UHP-FRC, several types of macro steel fibers, e.g., hooked-end (H-fiber), twisted (T-fibers), half-hooked (HH-fiber), and crimped (C-fiber), have been developed worldwide [19-23], as illustrated in Fig.1. Fibers play an important role in compensating for the deficiency and improving the performance of concrete because the high bonding of steel fiber with the matrix is very effective in controlling the micro-cracking mechanism, providing an improved resistance in terms of smaller crack openings at peak load [24]. Besides, using steel fiber in concrete increases the wet and dry densities of concrete. Because the density of steel fiber is more than the density of concrete [25]. The inclusion of steel fibers to the UHPC matrix significantly improves its tensile strength, post-cracking ductility, energy absorption capacity, and toughness. Steel fibers are capable of controlling crack opening and propagation by crossing their paths with the help of transferring applied stress between the fibers and the matrix through the interfacial bond [26, 27]. In addition to the fiber content, the individual pullout behavior of the activated fibers crossing a crack is also a significantly influential factor that affects the performances of UHPFRC composites. Therefore, the improved performance of UHPC is not only associated with the total amount of fibers but also the bond relationship between the individual fiber and the matrix. The fiber/matrix bond behavior is commonly assessed using the fiber pullout test.

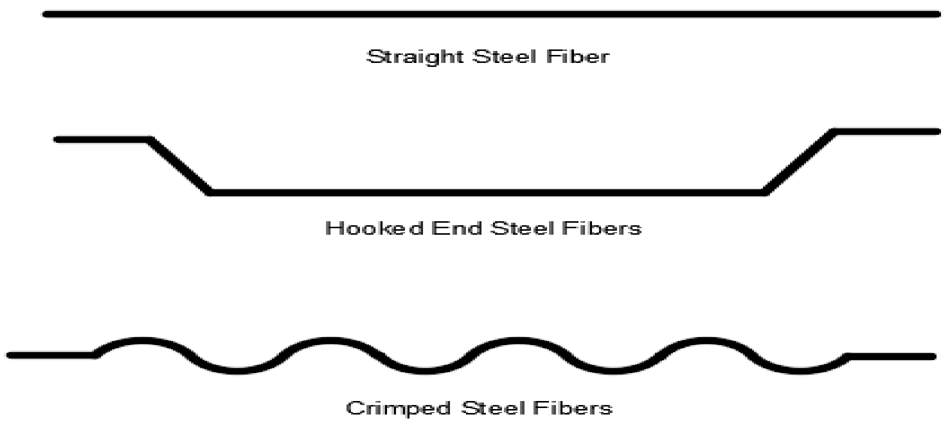


Fig.1 Common Types of Steel Fibers

Fiber pullout tests are adopted to investigate the steel fiber anchorage mechanism in a concrete matrix. The specimens used for pullout tests are generally characterized by a matrix form with discontinuities that run thru the whole transverse section. The two parts of the specimen are joined by one or more steel fibers. The test condition consists of fixing one end and applying the load to the other end so that the two-part can be separated, while the applied load and separation are recorded during the test process. However, in the case of only one-half of the specimen being used, the end of the fiber is left free, while the other end is pulled. The most commonly used specimens include dog-bone, half-dog-bone, prismatic, cubic, and cylindrical. Each type of specimen has a particular grip system. For instance, dog-bone specimens are fixed with rigid clamps designed with a special shape so that they can be coupled to the enlarged ends [28–30]. In the case of half-bone specimens, one end is fixed with the same type of rigid clamp, and on the other end, the fiber is pressed with a plane clamp, applying lateral pressure [31, 32]. Prismatic specimens are held with parallel faces clamps [33]. Cubic and cylindrical specimens are held with rings [34–37]. Some researchers used adhesives to fix the specimen body to the load system [38, 39]. This system has the advantage of avoiding lateral stresses that can distort pull-out responses [34].

In the past few decades, extensive experimental programs have been conducted to evaluate the steel fiber pullout strength behavior of NC and HSC [40, 41]. Different physical parameters such as fiber geometry, orientation, tensile strength, embedded length, and mortar strength have been evaluated to clarify their effect on the pullout bond strength of the concrete matrix [37, 42-44]. With the growing application of UHPC in modern construction, several experimental, analytical, and numerical studies have been devoted to simulating the pullout performance of various kinds of fibers focusing on the mechanism of bond strength between the steel fibers and the UHPC matrix. However, none of these studies provide an extensive evaluation that covers a wide range of influential parameters on the pullout bond strength of steel fibers from UHPC. Therefore, it is essential to compile the available experimental data on the pullout bond strength of steel fibers embedded in UHPC from the literature. This information can be used to understand the effect of fibers type, volume fractions, and embedded length on

the pullout strength of the UHPC matrix by covering a wide range of parameters.

2.0 Experimental Research on Pullout Behavior of Steel Fibers in UHPC

2.1 Variation of Parameters in Database

This section evaluates the distribution of key parameters affecting the pullout performance of steel fibers embedded in ultra-high performance concrete (UHC) over the database. The steel fiber types that have been utilized in the database include straight fibers, hooked-end fibers, twisted fibers, and half hooked-end fibers denoted as S-fiber, H-fibers, T-fibers, and HH-fibers. Different dimensions of steel fibers have been used, including fibers with lengths (l_f) of 13, 19.5, 25, 25.4, 26.2, 30, and 60 mm, and diameters (d_f) of 0.2, 0.3, 0.35, 0.375, 0.38, 0.4, 0.5, and 0.9 mm. Different aspect ratios (l_f/d_f) of steel fibers have also been adopted, including 50°, 60, 62.5, 65, 66.7, 71.4, 79, 80, 97.5, 100, and 125. In addition, different fiber volume fractions (V_f) have been added to the UHPC matrix available in the database (i.e. 1, 2, 3, 4, and 7%). Besides, the effect of fiber embedded length (l_e) (i.e. 5, 6, 6.5, 9.75, 10, 15, and 20) has been evaluated, with the most frequently used embed length in the database being 10mm. Furthermore, the influence of various inclination angles (θ) (i.e. 0°, 10°, 15°, 20°, 30°, 40°, 45°, and 60°) has been investigated in the database. Fiber spacing (S) (i.e. 1, 1.2, 1.9, 2.3, 2.7, and 3.3 mm) was considered in the database. Moreover, the effect of a wide range of loading rates on the pullout behavior of steel fibers embedded in UHPC has been assessed along with two types of test configuration (i.e. single and multiple fiber pullout tests.

2.2 Development of a Database

As shown in Table 1, the database developed for this study approximately contains more than 150 tests of UHPC specimens with various shapes and different types of fibers, collected from numerous studies [45-56], which have covered the bond properties of a fiber pullout test. D-Y. Yoo et. al. [45] examined the mechanical properties and pullout behavior of ultra-high-performance fiber-reinforced cementitious composites (UHPFRCC). Four different volume fractions (V_f) of 1, 2, 3, and 4 were utilized. They reported that the addition of steel fibers can provide better performance in terms of average and equivalent bond strengths and pullout energy. Y-S. Tai et. al. [46] also evaluated the mechanical performance of high-performance steel fibers embedded in UHPC at varied pullout speeds. Five different types of steel fiber were used, including straight, smooth steel fibers

(2 types), hooked steel fibers, and twisted steel fibers (2 types). Five rates ranging from quasi-static (0.018 mm/s) to impact rates (1800 mm/s) were used for pullout tests. The authors explored the influence of a reduced amount of glass powder (GP) on pullout behavior. Based on the findings, they indicated that the pullout behavior of all types of steel fibers shows a progressive increase in rate sensitivity concerning increasing the pullout speed and shows a significant increase during the impact loading where it was most prominent in the smooth and twisted steel fibers and least in the hooked fibers. In addition, M. Xu et. al. [47] examined the impact of loading rate on the pullout response of single fibers embedded in PC. Four high-strength steel fiber types including straight smooth brass-coated with a diameter of 0.2 mm and 0.38 mm, half hooked-end with a diameter of 0.38 mm, and twisted steel fibers with an equivalent diameter of 0.3 mm were utilized. The influence of fiber embedded angles on the loading rate sensitivity of steel fiber pullout behavior is investigated. Three fiber embedment angles, 0°, 20°, and 45°, are considered. The loading was applied in rates ranging from 0.025 mm/s (quasi-static) to 25 mm/s (seismic). Based on the results, they found that half hooked-end steel fibers showed the highest loading rate sensitivity of all other steel fibers. They also reported that there is a correlation between fiber embedment angle and loading rate sensitivity of steel fiber pullout behavior. In another study, D-Y. Yoo. et. al. [48] again evaluated the influence of steel fiber type on the fiber pullout behavior of high-performance fiber-reinforced cementitious composites (HPFRCC). Two types of steel fibers including straight and hooked-end steel fibers were utilized with three different matrix strengths. The authors reported that the hooked-end fibers exhibited higher bond strengths and pullout work than the straight fibers, but at large slips, they showed less shear stress at the interface than their counterparts. They indicated that straight steel fibers were more effective in improving the pullout performance with the matrix strength than hooked-end steel fibers. M. Roy. et. al. [49] experimentally studied the impact of steel fiber volume fraction (V_f) and orientation on the pullout performance of steel reinforcement bars embedded in UHPC. High-strength steel fibers having a diameter of 0.2 mm and a length of 13 mm with a corresponding aspect ratio of 65 and a slightly deformed mid-section were utilized. Four values of (V_f) including 0, 1, 2, and 3% were added to the concrete matrix. They reported that UHPC with steel fibers oriented perpendicular to the direction of load showed the highest pullout load while UHPC with steel fibers oriented parallel to the direction of load provided the lowest pullout load. However, the randomly oriented steel fibers gave values of the pullout load in between the parallel and perpendicular oriented steel fibers with respect to the direction of the load. Y.Y.Y Cao and Q.L. Yu [50] evaluated the pullout behavior of hooked-end steel fibers from the UHPC matrix. Various inclination angles were used taking into consideration steel fibers' dimension and embedded length. They found that the smaller diameter hooked-end steel fibers provided a higher performance where it showed the best performance under a pullout inclination angle of 0°. Chun B. and D-Y. Yoo [51] also studied the influence of hybrid macro and micro steel fibers on the pullout and tensile performance of UHPC. In their study, five different contents of the macro steel fibers with the micro steel fiber were utilized including 0, 0.5, 1.0, 1.5, and 2.0%. The authors observed that the average bond

strength and normalized pullout energy of the macro straight steel fibers embedded in the UHPC matrix were enhanced after their replacement with microfibers. On the contrary, those of the hooked-end and twisted macro steel fibers were reduced in accordance with the replacement ratio. It was also indicated that replacement of the macro fibers with the microfibers in the hooked and twisted fiber resulted in lower fiber efficiency ratios, while similar efficiency ratios were shown in the case of the macro straight steel fibers. J. Qi et al. [52] carried out a systematic evaluation of the pullout behavior of straight and hooked-end steel fibers embedded in UHPC using a single fiber pullout test. In their research, three types of steel fibers including straight fiber and hooked-end fibers (2 types), were aligned with respect to the loading direction at various inclination angles of 0°, 30°, and 45°. They reported that the straight steel fiber enhanced the average bond strength when the fiber embedded angle increased from 0° to 30° and 45° followed by hooked-end fibers. They also found that hooked-end fibers with a smaller diameter could be a better choice for structural applications. J-J. Kim and D-Y. Yoo [53] examined the influence of steel fiber shape and distance between fibers on the pullout performance of steel fibers embedded in the UHPC matrix. They utilized three different types of steel fibers including straight, hooked-end, and twisted with distances between fibers of 1%, 2%, and 7% values of V_f as well as single fiber and bundle fibers. The authors reported that the twisted steel fiber gave the greatest pullout resistance, followed by the hooked-end and straight steel fibers. They also found that using multiple steel fibers resulted in lower bond strength as compared to single fiber with neglecting the effect of fiber type and distance between fibers. In a recent study, D-Y. Yoo et. al. [54] examined the influence of steel fiber type on the pullout and tensile behavior of ultra-high-performance fiber-reinforced concrete (UHPFRC) where, four different types of steel fiber including straight, twisted, hooked-end, and half hooked-end, were adopted along with various fiber inclination angles ranging from 0°to 60°. They indicated that better pullout performance was attained in the deformed (twisted, hooked-end, and half hooked-end) steel fibers in comparison to that of the straight steel fiber. They observed that inclined steel fiber at 30° or 45° provided the highest bond strengths of all steel fiber types. They also noticed that the hooked-end steel fibers attained the highest bond strengths at all inclination angles, while the twisted and half-hooked steel fibers exhibited the highest pullout energies at aligned and highly inclined (45° and 60°) conditions, respectively. In another research, D-Y. Yoo and S. Kim [55] investigated the pullout performance of various types of steel fibers embedded in UHPC under static and impact loading conditions. Four types of steel fibers include straight, hooked-end, twisted, and half hooked-end. Three different loading rates were applied by static and impact pullout test machines. To evaluate the impact of inclination angle on the pullout response, four inclination angles of 0°, 30°, 45°, and 60° were utilized. They reported that the hooked-end and twisted steel fibers provided the highest average bond strength for static and impact loads, respectively, while the straight steel fibers provided the lowest bond strength at all inclination angles. They also found that half-hooked fibers were very effective when they were inclined, with maximum effectiveness at an inclination angle of 45° as compared to straight and highly deformed steel fibers. They also mentioned that using the twisted and half hooked-end steel fibers was more effective in static pullout energies than the hooked and straight steel fibers. More recently, H. Zhang et. al. [56] studied the effects of fiber shape and curing conditions on the pullout behavior of steel fibers from the UHPC matrix, prepared with Granite powder (GP) completely replaced by quartz powder (QP) by a single-fiber pullout test. Five types of steel fibers including straight fiber, single and double hooked-end steel fibers, corrugated steel (2 types) are utilized. They investigated the influence of three curing conditions including standard curing (SC), warm water curing (WWC), and autoclaved curing (AC) on the pullout behavior of steel fibers from the prepared UHPC matrix. They found that the replacement of QP by GP can enhance the pullout performance of both straight and smooth steel fiber. They also indicated that using WWC and AC curing conditions enhanced the peak pullout load, the average bond strength, the pullout energy, and the fiber utilization rate of the S fiber and most deformed fibers in comparison with SC conditions. But, as the brittleness of failure by fiber fracture also increases, Besides, deformed fibers demonstrated superior pullout performance, as compared to the straight steel fibers. However, the excessively deformed fibers such as the more corrugated fiber with dense waves tend to fracture when the cement matrix is cured under WWC and AC.

3.0 Results and Discussion

3.1 Evaluation Parameter

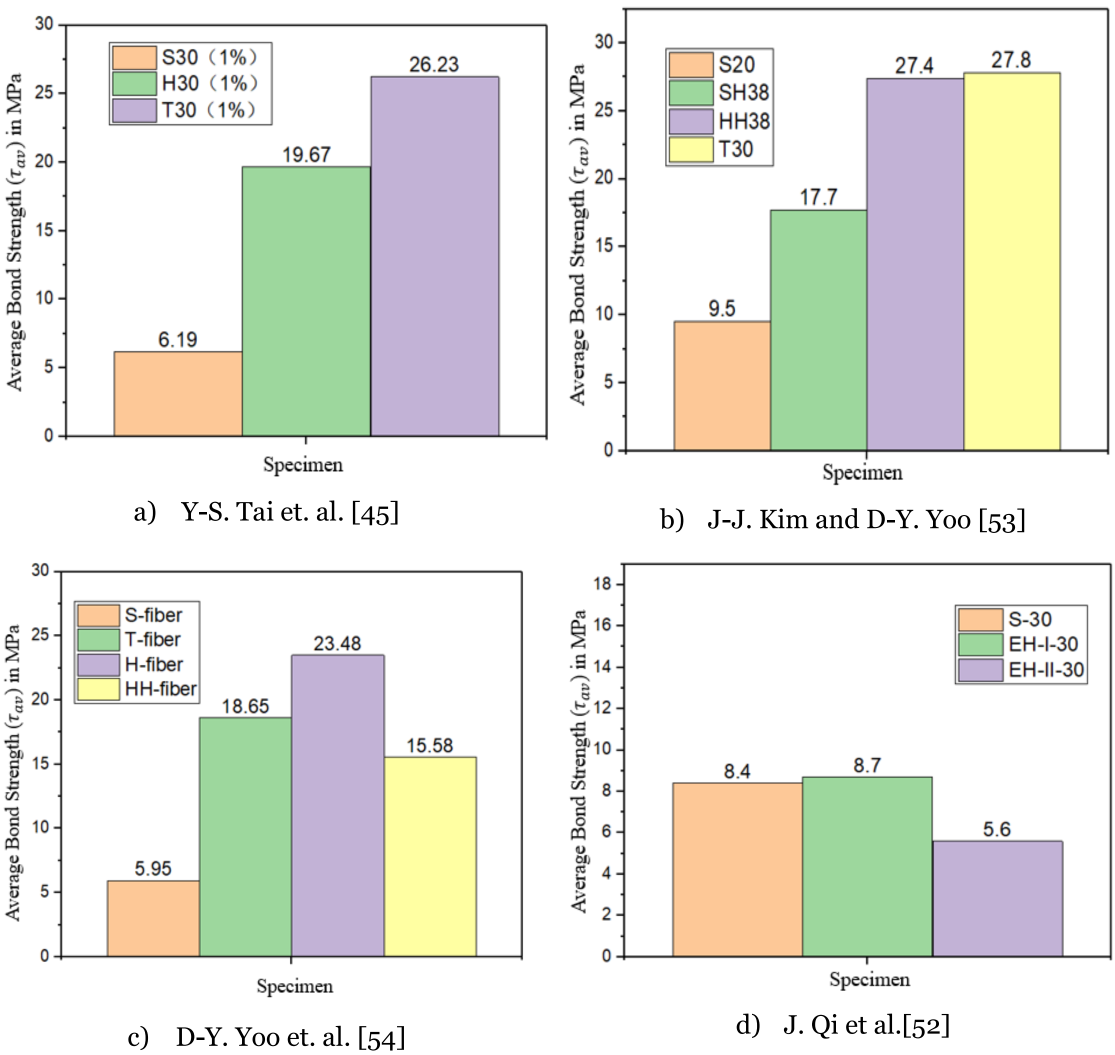
In order to assess the effect of fiber type and geometry, fiber volume fraction (V_f), embedded length (l_e), and inclination angle (θ) on the interfacial bond behavior, the average bond strength (τ_{av}) is utilized. Assuming that the bond strength is constant along the entire fiber embedded length, the average bond strength is described as the interfacial shear stress when the pullout load reaches its maximum value. It can be determined using the expression in Eq. (1), given by [57]:

$$\tau_{av} = \frac{P_{Max}}{\pi d_f L_e} \tag{1}$$

in which, d_f is the steel fiber diameter, and $L_e$is the initial embedded length of steel fiber.

3.2 Effects of Steel Fiber Types and Geometry.

Fig.2 shows the effect of various types of steel fibers including the straight, twisted, hooked-end, and half-hooked-end fibers. It can be observed from Fig. 2a that the twisted fiber exhibited the highest pullout performance, followed by hooked-end and straight fibers, respectively, which is consistent with the findings from Wille and Naaman [43]. Therefore, it could be found that the mechanical anchorage of the commercial hooked fiber is excessive in the plain UHPC matrix attributing to its very high strength and brittleness. Comparing the bond strength behavior between SH-fiber ($d_f = 0.38\ mm$), and S-fiber ($d_f = 0.2\ mm$), as shown in Fig. 2b suggests that a decrease in diameter increases the bond strength of straight steel fibers embedded in the ultra-high-strength matrix. On the contrary, it was observed that the effects of aligned steel fiber types on average bond strength can be ordered as H-fiber >T-fiber > HH-fiber > S-fiber, as can be seen from Fig. 2c-2d. The bond strength of the H-fiber slightly increased slightly because the exterior end hooks had bent in the opposite direction. The H- fibers could be pulled out from the UHPC matrix after complete bending of the plastic hinge at the end hooks, resulting in a great improvement in average bond strength in comparison with that of the S-fiber [58]. During pullout, untwisting T-fibers cause local pressure on the matrix, which can crush it or cause radial or longitudinal micro splitting along the fiber length [46]. The T-fiber can also generate additional pullout resistance by twisting torque due to pre-twisting along the fiber length and its quadrangular cross-sectional shape. The twisting torque causes local pressure at the interface between the fiber and concrete matrix, leading to the formation and disperse of micro-splitting cracks in the surrounding matrix. These splitting cracks usually initiate at the fiber exit and continuously spread toward the fiber end. It can be seen from Fig. 1d that specimens with hooked-end fibers with a smaller diameter attained the highest bond strength as compared to their counterparts of larger diameter (EH-30-II), which also shows a low bond strength as compared to the specimen with straight fiber (S-30). Thus, smaller diameter hooked-end steel fibers could be a better choice for structural applications. Overall, it can be demonstrated that the deformed steel fibers clearly provided higher average bond strengths than straight fibers. This could be attributed to the impact of mechanical anchorage obtained at the end hook for the hooked and half-hooked fibers and throughout the entire embedment length by torsion in the case of twisted fiber.



a) Y-S. Tai et. al. [45]

b) J-J. Kim and D-Y. Yoo [53]

c) D-Y. Yoo et. al. [54]

d) J. Qi et al.[52]

Fig. 2. Average Bond Strength (τ_{av}) versus Steel Fiber Types

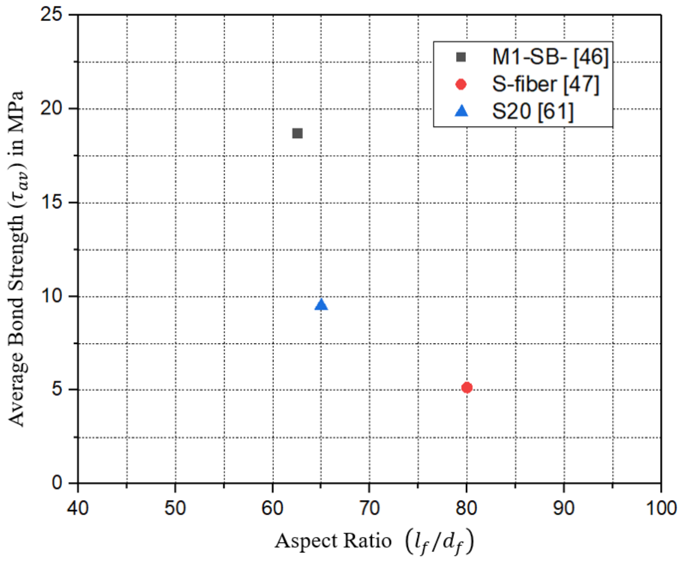
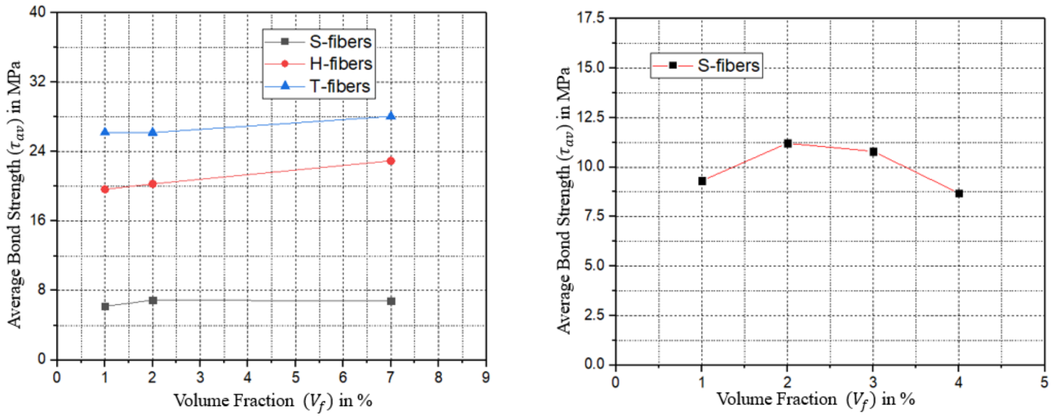


Fig. 3. Average Bond Strength (τ_{av}) versus Aspect Ratio (l_f/d_f) [46, 47, 61]

The effect of aspect ratio (l_f/d_f) on the average bond strength is shown in Fig. 3. It can be seen that using steel fibers with a smaller aspect ratio provides higher bond strength between the steel fiber and UHPC matrix. This could be attributed to the strong bond provided by steel fiber of large diameter.

3.3 Effect of Steel Fibers Volume Fraction

It can be seen from Fig. 4 that the average bond strength increases with increasing the volume fraction of fibers. As compared with the 1% volume fraction of straight, hooked, and twisted steel fibers, a volume fraction of 2% showed an increase in bond strength of specimens. The highest pullout bond strength was obtained from the inclusion of a 7% steel fibers volume fraction in the UHPC matrix. Therefore, it is evident that the inclusion of a higher volume fraction can provide better pullout performance in terms of bond strength. This could be due to the multiple discontinuous steel fibers provided by a higher volume fraction of steel fibers, which can provide multiple bridges in the cracked sections of UHPC, contributing to the improvement of steel transfer and enhancement of average pullout bond strengths of steel fibers from UHPC matrix. However, an average pullout bond strength of 11.21 MPa was obtained by increasing of fiber volume fraction in the UHPC matrix up to 2%. When the steel fiber volume fractions increase beyond 2%, the average bond strength decreases to 10.8 and 8.68 MPa at volume concentrations of 3% and 7%, as can be seen in Fig.4. This could be attributed to the creation of voids fraction and lower composite shrinkage of higher fiber volume fraction, which leads to a reduction in radial confinement pressure of the composites [59].



a) J-J. Kim and D-Y. Yoo [53] b) Y.Y.Y Cao and Q.L. Yu [45]

Fig. 4. Average Bond Strength (τ_{av}) versus Steel Fiber Volume Fraction (V_f).

3.4 Effects of Embedded Length

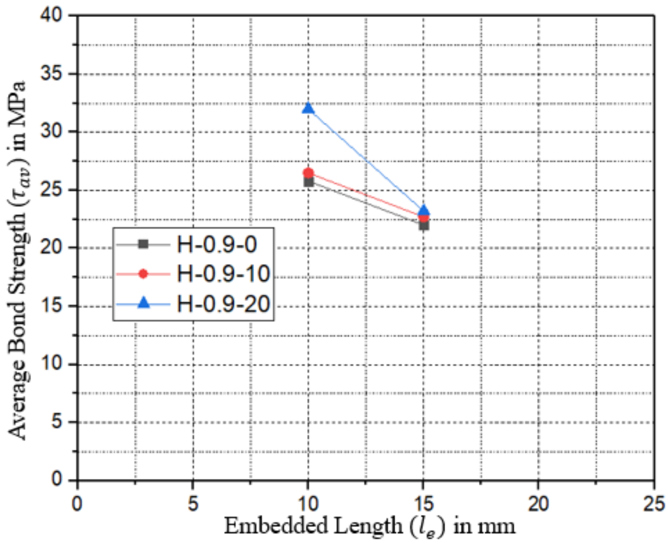


Fig. 5. Average Bond Strength (τ_{av}) versus Steel Fiber Embedded length (L_e) for Hooked-end steel fibers [50]

The embedded length (L_e) of steel fibers is an essential factor that influences the overall pullout behavior of the steel fiber embedded in UHPC. It was demonstrated that increasing the embedded length of steel fiber could greatly contribute to the enhancement of pullout resistance resulting in increased bond strength between the UHPC matrix and steel fibers. It was also found that since straight steel fibers are initially in chemical adherence with the surrounding UHPC matrix, hence using an increased embedded length in straight steel fibers could increase the contact surface area with the UHPC matrix. However, this cannot be applied in the case of deformed steel fibers such as twisted (T-fiber) hooked-end (H-fiber) steel fibers. This could be due to the fact that the bond is controlled by the mechanical anchorage of the end-hook rather than the physio-chemical bond in a straight portion [1]. Therefore, using a shorter embedded length in hook-type steel fibers could result in higher bond strength, as shown in Fig. 5.

4.0 Conclusion

In this study, an experimental database is gathered from literature in order to investigate the influence of fiber type, volume fraction, and embedded length on the fiber pullout strength from the UHPC matrix. Four different steel fiber types including straight, twisted, hooked-end, and half hooked-end fibers were used in various literature of databases along with fiber volume fractions of 1, 2, 3, 4, and 7%. Based on the analysis of these key parameters available in the collected research database, the following conclusions are drawn:

a) It was found that the effects of aligned steel fiber types on average bond strength can be ordered as H-fiber > T-fiber > HH-fiber > S-fiber. The H-fibers could be pulled out of the UHPC matrix after complete bending of the plastic hinge at the end hooks, resulting in a great improvement in average bond strength in comparison with that of the S-fiber. Besides, the T-fiber can generate additional pullout resistance by twisting torque due to pre-twisting along the fiber length and its quadrangular cross-sectional shape.
b) It was observed that a decrease in diameter increases the bond strength of straight steel fibers embedded in the ultra-high-strength matrix. Thus, hooked-end fibers with a smaller diameter could be a better choice for structural applications.
c) Using smaller embedded lengths in deformed steel fibers could result in an improvement in bond strength. This could be due to the fact that the bond is controlled by the mechanical anchorage of the end-hook rather than the physio-chemical bond in the straight portion. Conversely, increasing the embedded length of steel fiber could greatly contribute to the enhancement of pullout resistance, resulting in increased bond strength between the UHPC matrix and steel fibers.
d) The average pullout bond strengths were found to be enhanced with the increase in fiber volume fraction in the UHPC matrix up to 2% and decreased with increasing the fiber volume fraction beyond 2%. This could be attributed to the creation of a void fraction and lower composite shrinkage of a higher fiber volume fraction, which leads to a reduction in the radial confinement pressure of the UHPC composites.

Overall, it is demonstrated that the deformed steel fibers clearly provide higher average bond strengths than straight fibers.

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Table 1: Research Database for this study

Ref.	ID	Steel Fibers											f_c' (MPa)	Test configuration	V (mm/s)	Key parameters	τ_{av} (MPa)
		Type	L_f (mm)	d_f (mm)	AR (mm)	L_{eh} (mm)	P	θ_h	V_f %	S (mm)	θ°	L_e (mm)					
[45]	S30 (1%)	S-fibers	30	0.3	100				1	2.7	0	10	190.2	Multiple fibers	0.018	• Types of steel fibers • Fiber volume fractions V_f • Distance between fibers • Fiber bundling	6.19
	S30 (2%)		30	0.3	100				2	1.9	0	10	190.2	Multiple fibers	0.018		6.91
	S30 (7%)		30	0.3	100				7	1	0	10	190.2	Multiple fibers	0.018		6.81
	S30 (bundle)		30	0.3	100				-	0	0	10	190.2	Multiple fibers	0.018		6.70
	S30 (single)		30	0.3	100				-	-	0	10	190.2	Single Fiber	0.018		8.82
	H30 (1%)	H-fibers	30	0.375	80				1	3.3	0	10	190.2	Multiple fibers	0.018		19.67
	H30 (2%)		30	0.375	80				2	2.3	0	10	190.2	Multiple fibers	0.018		20.30
	H30 (7%)		30	0.375	80				7	1.2	0	10	190.2	Multiple fibers	0.018		22.95
	H30 (bundle)		30	0.375	80				-	0	0	10	190.2	Multiple fibers	0.018		18.76
	H30 (single)		30	0.375	80				-	-	0	10	190.2	Single Fiber	0.018		27.18
	T30 (1%)	T-fibers	30	0.3	100				1	2.7	0	5	190.2	Multiple fibers	0.018		26.23
	T30 (2%)		30	0.3	100				2	1.9	0	5	190.2	Multiple fibers	0.018		26.21
	T30 (7%)		30	0.3	100				7	1	0	5	190.2	Multiple fibers	0.018		28.08
	T30 (bundle)		30	0.3	100				-	0	0	5	190.2	Multiple fibers	0.018		24.43
	T30 (single)		30	0.3	100				-	-	0	5	190.2	Single Fiber	0.018		38.32
[46]	BCH10	H-fibers	30	0.375	80	3.5	-	-	-	-	0	10	156	Single Fiber	5	• Loading rate • Embedded length	16.14
			30	0.375	80	3.5	-	-	-	-	0		156	Single Fiber	50		17.75
			30	0.375	80	3.5	-	-	-	-	0		156	Single Fiber	500		19.46

			30	0.375	80	3.5	-	-	-	-	0		156	Single Fiber	1000		19.95
	BCH10		30	0.375	80	3.5	-	-	-	-	0	15	156	Single Fiber	5		13.82
			30	0.375	80	3.5	-	-	-	-	0		156	Single Fiber	50		14.17
			30	0.375	80	3.5	-	-	-	-	0		156	Single Fiber	500		15.50
			30	0.375	80	3.5	-	-	-	-	0		156	Single Fiber	1000		16.82
[49]	S-fiber	S-fiber	13	0.2	65	-	-	-	-	-	0	10	128.1	Single Fiber	0.018	• Types of steel fibers	5.95
			13	0.2	65	-	-	-	-	-	30	10	128.1	Single Fiber	0.018	• Inclination angles	6.91
			13	0.2	65	-	-	-	-	-	45	10	128.1	Single Fiber	0.018		6.57
			13	0.2	65	-	-	-	-	-	60	10	128.1	Single Fiber	0.018		5.92
	T-fiber	T-fiber	30	0.3	100	-	-	-	-	-	0	5	128.1	Single Fiber	0.018		18.65
			30	0.3	100	-	-	-	-	-	30	5	128.1	Single Fiber	0.018		19.02
			30	0.3	100	-	-	-	-	-	45	5	128.1	Single Fiber	0.018		18.14
			30	0.3	100	-	-	-	-	-	60	5	128.1	Single Fiber	0.018		17.16
	H-fiber	H-fiber	30	0.375	80	-	-	-	-	-	0	10	128.1	Single Fiber	0.018		23.48
			30	0.375	80	-	-	-	-	-	30	10	128.1	Single Fiber	0.018		24.42
			30	0.375	80	-	-	-	-	-	45	10	128.1	Single Fiber	0.018		24.31
			30	0.375	80	-	-	-	-	-	60	10	128.1	Single Fiber	0.018		21.39
	HH-fiber	HH-fiber	25	0.375	66.7	-	-	-	-	-	0	10	128.1	Single Fiber	0.018		15.58
			25	0.375	66.7	-	-	-	-	-	30	10	128.1	Single Fiber	0.018		20.77
			25	0.375	66.7	-	-	-	-	-	45	10	128.1	Single Fiber	0.018		21.01
			25	0.375	66.7	-	-	-	-	-	60	10	128.1	Single Fiber	0.018		16.50
[50]	S-0	S-fibers	13	0.2	65	-	-	-	-	-	0	6.5	151.5	Single Fiber	0.017	• Fiber embedded	11.7
	S-30		13	0.2	65	-	-	-	-	-	30	6.5	151.5	Single Fiber	0.017	angle,	17.1
	S-45		13	0.2	65	-	-	-	-	-	45	6.5	151.5	Single Fiber	0.017	• Fiber type,	20.6
	EH-I-0	H-fibers-I	13	0.2	65	1.5	-	-	-	-	0	6.5	151.5	Single Fiber	0.017	• Fibber geometry	12.2
	EH-I-30		13	0.2	65	1.5	-	-	-	-	30	6.5	151.5	Single Fiber	0.017		15.0

	EH-I-45		13	0.2	65	1.5	-	-	-	-	45	6.5	151.5	Single Fiber	0.017		16.8
	EH-II-0	H-fibers-11	25	0.35	71.4	5	-	-	-	-	0	12.5	151.5	Single Fiber	0.017		9.2
	EH-II-30		25	0.35	71.4	5	-	-	-	-	30	12.5	151.5	Single Fiber	0.017		10.8
	EH-II-45		25	0.35	71.4	5	-	-	-	-	45	12.5	151.5	Single Fiber	0.017		10.1
[51]	M1-SA	S-fibers	25	0.2	125	-	-	-	-	-	0	6.0	184.9	Single Fiber	0.018	• Types of high-strength steel fiber • Varying amounts of glass powder • Loading rates	5.2
			25	0.2	125	-	-	-	-	-	0	6.0	184.9	Single Fiber	1.8		5.7
			25	0.2	125	-	-	-	-	-	0	6.0	184.9	Single Fiber	18		6.5
			25	0.2	125	-	-	-	-	-	0	6.0	184.9	Single Fiber	180		9
			25	0.2	125	-	-	-	-	-	0	6.0	184.9	Single Fiber	1800		10.9
	M1-SB		25	0.4	62.5	-	-	-	-	-	0	6.0	184.9	Single Fiber	0.018		18.7
			25	0.4	62.5	-	-	-	-	-	0	6.0	184.9	Single Fiber	1.8		20.0
			25	0.4	62.5	-	-	-	-	-	0	6.0	184.9	Single Fiber	18		21.1
			25	0.4	62.5	-	-	-	-	-	0	6.0	184.9	Single Fiber	180		22.5
			25	0.4	62.5	-	-	-	-	-	0	6.0	184.9	Single Fiber	1800		27.4
	M2-SB		25	0.4	62.5	-	-	-	-	-	0	6.0	171.2	Single Fiber	0.018		14.5
			25	0.4	62.5	-	-	-	-	-	0	6.0	171.2	Single Fiber	1.8		14.4
			25	0.4	62.5	-	-	-	-	-	0	6.0	171.2	Single Fiber	18		14.7
			25	0.4	62.5	-	-	-	-	-	0	6.0	171.2	Single Fiber	180		17.0
			25	0.4	62.5	-	-	-	-	-	0	6.0	171.2	Single Fiber	1800		17.2
	M1-H	H-fibers	30	0.38	79	-	-	-	-	-	0	6.0	184.9	Single Fiber	0.018		23.0
			30	0.38	79	-	-	-	-	-	0	6.0	184.9	Single Fiber	1.8		25.8
			30	0.38	79	-	-	-	-	-	0	6.0	184.9	Single Fiber	18		27.8
			30	0.38	79	-	-	-	-	-	0	6.0	184.9	Single Fiber	180		30.3
			30	0.38	79	-	-	-	-	-	0	6.0	184.9	Single Fiber	1800		35.7
	M1-TA	T-fibers	25.4	0.5	50	-	8	-	-	-	0	6.0	184.9	Single Fiber	0.018		21.7
			25.4	0.5	50	-	8	-	-	-	0	6.0	184.9	Single Fiber	1.8		28.1

			25.4	0.5	50	-	8	-	-	-	0	6.0	184.9	Single Fiber	18		28.3
			25.4	0.5	50	-	8	-	-	-	0	6.0	184.9	Single Fiber	180		33.3
			25.4	0.5	50	-	8	-	-	-	0	6.0	184.9	Single Fiber	1800		43.9
[53]	S20	S-fibers	0.20	13	65						0	6.5	194	Single Fiber	0.025	• Loading rates	9.5
			0.20	13	65							6.5	194	Single Fiber	0.25	• Type if fibers	10.6
			0.20	13	65							6.5	194	Single Fiber	2.5	• Inclination angle	10.5
			0.20	13	65							6.5	194	Single Fiber	25		11.3
	SH38	H-fibers	0.38	30	79	4					0	6.5	194	Single Fiber	0.025		17.7
			0.38	30	79	4						6.5	194	Single Fiber	0.25		18.5
			0.38	30	79	4						6.5	194	Single Fiber	2.5		18.9
			0.38	30	79	4						6.5	194	Single Fiber	25		17.8
			0.38	30	79	4					20	6.5	194	Single Fiber	0.025		17.4
			0.38	30	79	4						6.5	194	Single Fiber	25		21.4
			0.38	30	79	4					40	6.5	194	Single Fiber	0.025		19.4
			0.38	30	79	4						6.5	194	Single Fiber	25		20.6
	HH38	HH-fibers	0.38	30	79	4					0	6.5	194	Single Fiber	0.025		27.4
			0.38	30	79	4						6.5	194	Single Fiber	0.25		30.7
			0.38	30	79	4						6.5	194	Single Fiber	2.5		32.3
			0.38	30	79	4						6.5	194	Single Fiber	25		35.1
	T30	T-fibers	30	0.3	100		8				0	6.5	194	Single Fiber	0.025		27.8
			30	0.3	100		8					6.5	194	Single Fiber	0.25		29.7
			30	0.3	100		8					6.5	194	Single Fiber	25		31.8
[54]	S13-MA	S-fibers	13	0.2	65						0	6.5	112.2	Single Fiber	0.4	• Type of fibers	7.69
	S19.5MA		19.5	0.2	97.5						0	9.75	112.2	Single Fiber	0.4	• Matrix strengths	7.21
	S30MA		30	0.3	100						0	15	112.2	Single Fiber	0.4		6.16
	S13-MB		13	0.2	65						0	6.5	152.5	Single Fiber	0.4		8.36

	S19.5MB		19.5	0.2	97.5						0	9.75	152.5	Single Fiber	0.4		7.43
	S30MB		30	0.3	100						0	15	152.5	Single Fiber	0.4		6.16
	S13-MC		13	0.2	65						0	6.5	190.2	Single Fiber	0.4		9.17
	S19.5MC		19.5	0.2	97.5						0	9.75	190.2	Single Fiber	0.4		8.29
	S30MC		30	0.3	100						0	15	190.2	Single Fiber	0.4		6.46
	H30MA	H-fibers	30	0.375	80						0	15	112.2	Single Fiber	0.4		11.36
	H30MB		30	0.375	80						0	15	152.5	Single Fiber	0.4		12.10
	H30MC		30	0.375	80						0	15	190.2	Single Fiber	0.4		7.29
[55]		S-fibers	30	0.2	65						0	10	150	Single Fiber	0.018	• Type of steel fibers	5.95
			30	0.2	65							10	150	Single Fiber	315.9	• Loading rates	12.00
			30	0.2	65							10	150	Single Fiber	511.1	• Inclination angle	17.02
			30	0.2	65						30	10	150	Single Fiber	0.018		6.91
			30	0.2	65							10	150	Single Fiber	454.7		14.98
			30	0.2	65							10	150	Single Fiber	514.6		19.34
			30	0.2	65						45	10	150	Single Fiber	0.018		6.57
			30	0.2	65							10	150	Single Fiber	534.6		14.33
			30	0.2	65							10	150	Single Fiber	660.8		15.82
			30	0.2	65						60	10	150	Single Fiber	0.018		5.92
			30	0.2	65							10	150	Single Fiber	779.2		12.80
			30	0.2	65							10	150	Single Fiber	1022.7		15.54
		H-fibers	30	0.375	80						0	10	150	Single Fiber	0.018		23.48
			30	0.375	80							10	150	Single Fiber	425.7		35.11
			30	0.375	80							10	150	Single Fiber	927.1		35.02
			30	0.375	80						30	10	150	Single Fiber	0.018		24.42
			30	0.375	80							10	150	Single Fiber	428.8		29.57
			30	0.375	80							10	150	Single Fiber	941.9		35.31

			30	0.375	80						45	10	150	Single Fiber	0.018		24.31
			30	0.375	80							10	150	Single Fiber	538.3		22.39
			30	0.375	80							10	150	Single Fiber	1131.4		28.91
			30	0.375	80						60	10	150	Single Fiber	0.018		21.39
			30	0.375	80							10	150	Single Fiber	595.8		22.94
			30	0.375	80							10	150	Single Fiber	1221.5		23.99
		T-fibers	30	0.3	100						0		150	Single Fiber	0.018		19.85
			30	0.3	100							5	150	Single Fiber	315.5		39.74
			30	0.3	100							5	150	Single Fiber	936.7		47.72
			30	0.3	100						30	5	150	Single Fiber	0.018		19.02
			30	0.3	100							5	150	Single Fiber	377.9		34.30
			30	0.3	100							5	150	Single Fiber	995.8		40.96
			30	0.3	100						45	5	150	Single Fiber	0.018		19.00
			30	0.3	100							5	150	Single Fiber	398.1		30.19
			30	0.3	100							5	150	Single Fiber	985.9		42.49
			30	0.3	100						60	5	150	Single Fiber	0.018		17.16
			30	0.3	100							5	150	Single Fiber	592.6		26.14
			30	0.3	100							5	150	Single Fiber	1159.0		33.65
		HH-fibers	25	0.375	66.7						0	10	150	Single Fiber	0.018		12.51
			25	0.375	66.7							10	150	Single Fiber	380.1		24.87
			25	0.375	66.7							10	150	Single Fiber	907.7		32.49
			25	0.375	66.7						30	10	150	Single Fiber	0.018		15.06
			25	0.375	66.7							10	150	Single Fiber	453.9		24.68
			25	0.375	66.7							10	150	Single Fiber	802.0		34.62
			25	0.375	66.7						45	10	150	Single Fiber	0.018		18.26
			25	0.375	66.7							10	150	Single Fiber	519.7		23.00

			25	0.375	66.7						10	150	Single Fiber	831.7		26.52
			25	0.375	66.7					60	10	150	Single Fiber	0.018		15.59
			25	0.375	66.7						10	150	Single Fiber	660.0		21.80
			25	0.375	66.7						10	150	Single Fiber	1718.0		24.51

Where, L_f is the length of steel fibers, d_f is the diameter of steel fibers L_{eh} is the length of end hook, P is the pitch of twisted fibers, θ_h is the angle of hook-end, V_f is the steel fibers volume fractions, S is the spacing/distance between fibers, θ is the embedded angle of steel fibers, L_e is the embedded length of steel fibers, f_c' is the compressive strength of UHPC, V is the loading rate, and τ_{av} is the average bond strength.